EXHIBIT A

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Filtering and tuning of class-E power amplifiers

by

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Abstract

This note investigates tuning techniques for a class-E power amplifier (PA) based upon a T-type output filter. It is shown that retuning of an ideal amplifier for 100-percent efficiency and the nominal power output can be accomplished by tuning only the drain-shunt capacitor and capacitor in the T network. Tunable inductors are not required, and the tuning capacitors are conveniently grounded on one side.

Indexing Terms

Amplifier, power, class-E
Amplifier, power, output filter

1. INTRODUCTION

Class-E operation of a power amplifier minimizes the losses due to drain-shunt capacitance. This makes class E desirable for high-efficiency amplification at UHF using standard RF-power transistors and at HF using low-cost devices in TO-247 packages. However, the necessity to tune several components in the output network for the frequency of operation is a significant disadvantage.

This note investigates tuning techniques based upon a T-type output filter (Figure 1). It is shown that retuning of a class-E PA with this output network can be accomplished by tuning only the drain-shunt capacitor C1 and the output capacitor C2. Tunable inductors are not required, and the tuning capacitors are conveniently grounded on one side. The capacitors can be standard mechanical "bread slicers", mechanical trimmers, or electronically tunable devices such as MOSFETs, *pin* diodes, or MMDCs [TR98-1].

The basis for tunability with only two components is illustrated in Figure 2. A class-E PA with optimum values of shunt capacitance and series reactance achieves unity efficiency for all load impedances along the diagonal line [1]. The locus of load impedances produced by a T network consisting of L1B, C2, and L2 that is retuned for the frequency of operation follows the $R = 1$ circle and is quite close to the $\eta = 1$ line over a frequency range of 2:1 or more. Consequently, only relatively small modifications of the load impedance are required to achieve unity efficiency.

2. TUNING VIA DRAIN-SHUNT CAPACITANCE

The well-known variation [2] of efficiency and power with series reactance is shown in Figure 3. The efficiency has a broad double peak, while the power output has a single narrow peak. Maximum output power and maximum efficiency occur for two different reactances. (All graphs are based upon $V_{DD} = 1$ and $R = 1$.)

The effect of varying the shunt susceptance B is shown in Figure 4 for several values of series reactance. For the ideal value of reactance (1.152), the efficiency curve has a broad double peak while the output power has a somewhat sharper peak.

Also included in Figure 4 are the curves for several other values of X. For $X < 1.152$, the efficiency has a broad peak as B is varied. However, it never reaches 100 percent. The output power increases slowly as B is increased. For $X > 1.152$, the efficiency has a double peak and the output power has a sharp peak located near the first peak in efficiency. This is a suboptimum high-efficiency mode similar to those discussed in [3].

The efficiency and power output achievable by retuning the shunt capacitor are shown in Figure 2. For $X < 1.152$ the improvement is negligible. However, $X > 1.152$, tuning the drain-shunt capacitor can restore 100-percent efficiency with an output power that is about 1.5-dB larger than nominal.

Reduction of the supply voltage to 0.85 times its value for nominal conditions gives the nominal output power (0.577).

The shunt susceptance required for maximum efficiency is shown as a function of X in Figure 5. For $X > 1.152$, B decreases rapidly. If the increased inductance is the result of an increase in frequency, the corresponding shunt capacitance must decrease even more quickly.

The peak drain current remains relatively constant for maximum-efficiency tuning of B when $X > 1.152$ (Figure 5). However, the peak drain voltage increases approximately linearly with X.

The drain-voltage waveforms for retuning with $X > 1.152$ (Figure 6) unfortunately have significant negative excursions. Sustaining the negative drain voltages requires adding a Schottky diode in series with the source. This has the obvious disadvantage of additional voltage drop (hence power loss) and additional inherent shunt capacitance. The storage time associated with other types of diodes may cause problems.

The intrinsic diode in a MOSFET PA prevents negative drain voltages, thus effectively shortening the off time. This has the potential advantage of automatically adjusting the off time to maintain 100-percent efficiency. However, the intrinsic diodes are not generally rated, and their turn-on renders the previously presented calculations inaccurate. Turn-on of the intrinsic diode can be avoided by diligent adjustment of drive amplitude and bias.

These results suggest that retuning of the drain capacitance can be used to restore efficiency and power output when load reactance is present. However, the duty ratio must change, hence either additional analysis or experimentation is required to quantify the tuning range.

3. T NETWORK

The T network is attractive for use with switching-mode PAs because it presents a high impedance to harmonics and can be retuned by a single adjustment (of its capacitor) [TR98-1]. Basically, it acts as two back-to-back L networks that match up and then back down. When retuned for the frequency of operation, its Q changes but its input remains resistive.

Tuning C2 Only

Figure 7 shows the variation of efficiency and power output when C2 is retuned with frequency so that the combination of L1B, C2, and L2 produces a resistive input impedance. The result is a nearly flat efficiency over a 2:1 frequency range. However, the output power varies over a 2:1 range. This is the classic $Q = 0$ case in [2] where only B_{opt} and X_{opt} affect performance.

The required variation of capacitance is shown in Figure 8. Capacitor C2 must change by a factor of 3 for a 2:1 variation in frequency [RN97-16].

The peak drain voltage is high for $f < 0.4f_0$, but reasonable for $f > f_0$.

The peak drain current is reasonable at all frequencies. The waveforms (Figures 52 and 53 of [RN88-55]) have small negative excursions for $f < f_0$.

Tuning Both C1 and C2

Variation of both C1 and C2 provides two degrees of freedom and therefore has the potential of controlling both efficiency and power output.

Computation of the optimum combination for C1 and C2 is somewhat difficult because there are an infinite number of combinations that yield $\eta = 1$. A possible method for solving this problem is to make contours of both efficiency and power output as functions C1 and C2. The combination that yields $\eta = 1$ and the nominal output power can then easily be found. Unfortunately, this sort of solution must be undertaken for each frequency of interest.

Nonetheless, simple manual iteration can be used to find solutions by moving away from known solutions in small steps. The results for $f = 0.5f_0$, $1.5f_0$, and $2f_0$ are shown as dots in Figure 7. It is apparent that both unity efficiency and nominal power output (that of an optimum PA at f_0) can be achieved over a 4:1 frequency range.

The variation of capacitance is not greatly different (Figure 8) from that required for ordinary retuning of the T network. The maximum voltage and current remain reasonable. The waveforms (Figure 9) include small negative voltages and currents, but the negative excursions are not large enough to pose a significant problem.

4. REFERENCES

[1] F. H. Raab, "Effects of VSWR upon the class-E RF-power amplifier," *Proc. RF Expo East '88*, Philadelphia, PA, pp. 299 - 309, Oct. 25 - 27, 1988. [TP88-1]

[2] F. H. Raab, "Effects of circuit variations on the class E tuned power amplifier," *IEEE J. Solid State Circuits*, vol. SC-13, no. 2, pp. 239 - 247, April 1978. [TP75-4]

[3] F. H. Raab, "Suboptimum operation of class-E RF power amplifiers," *Proc. RF Technology Expo '89*, Santa Clara, CA, pp. 85 - 98, Feb. 14 - 16, 1989. [TP88-5]

APPENDIX A. PROGRAMS

NUMBER	NAME	USE
FHR-826	CEX	Effect of load reactance upon class-E PA
FHR-827	CEB	Effect of shunt susceptance upon class-E PA
FHR-828	CEXT	Class-E PA with series reactance and tuning of shunt capacitance
FHR-534	CEWAVE	Waveforms of class-E PA
FHR-829	CET1	Class-E PA with T filter, single point
FHR-830	CET2	Class-E PA with T filter, frequency sweep

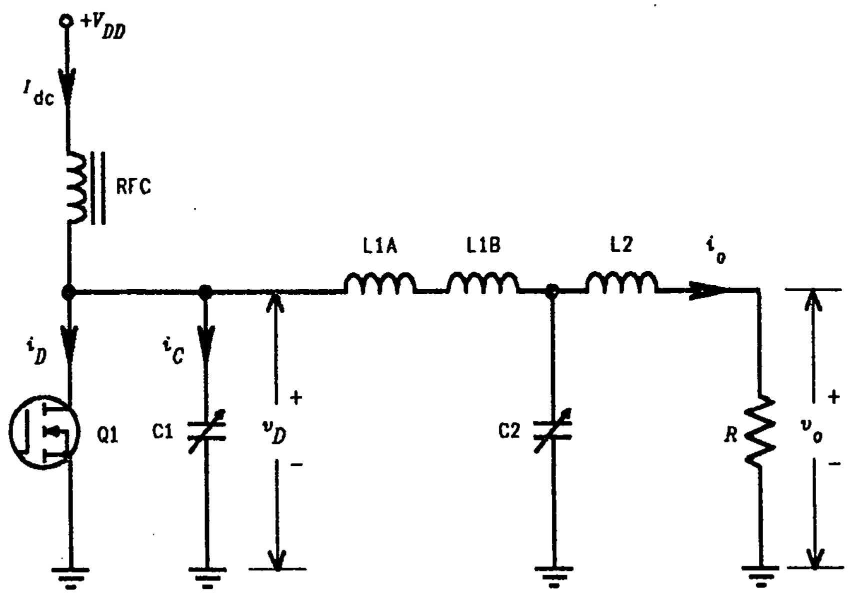

Figure 1. Class-E PA with T filter.

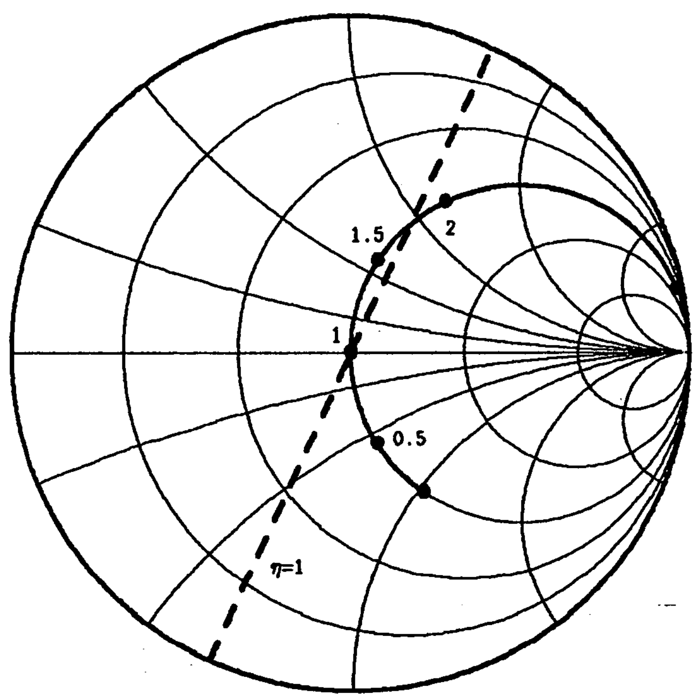

Figure 2. Impedances for η = 1 and at input of L1B.

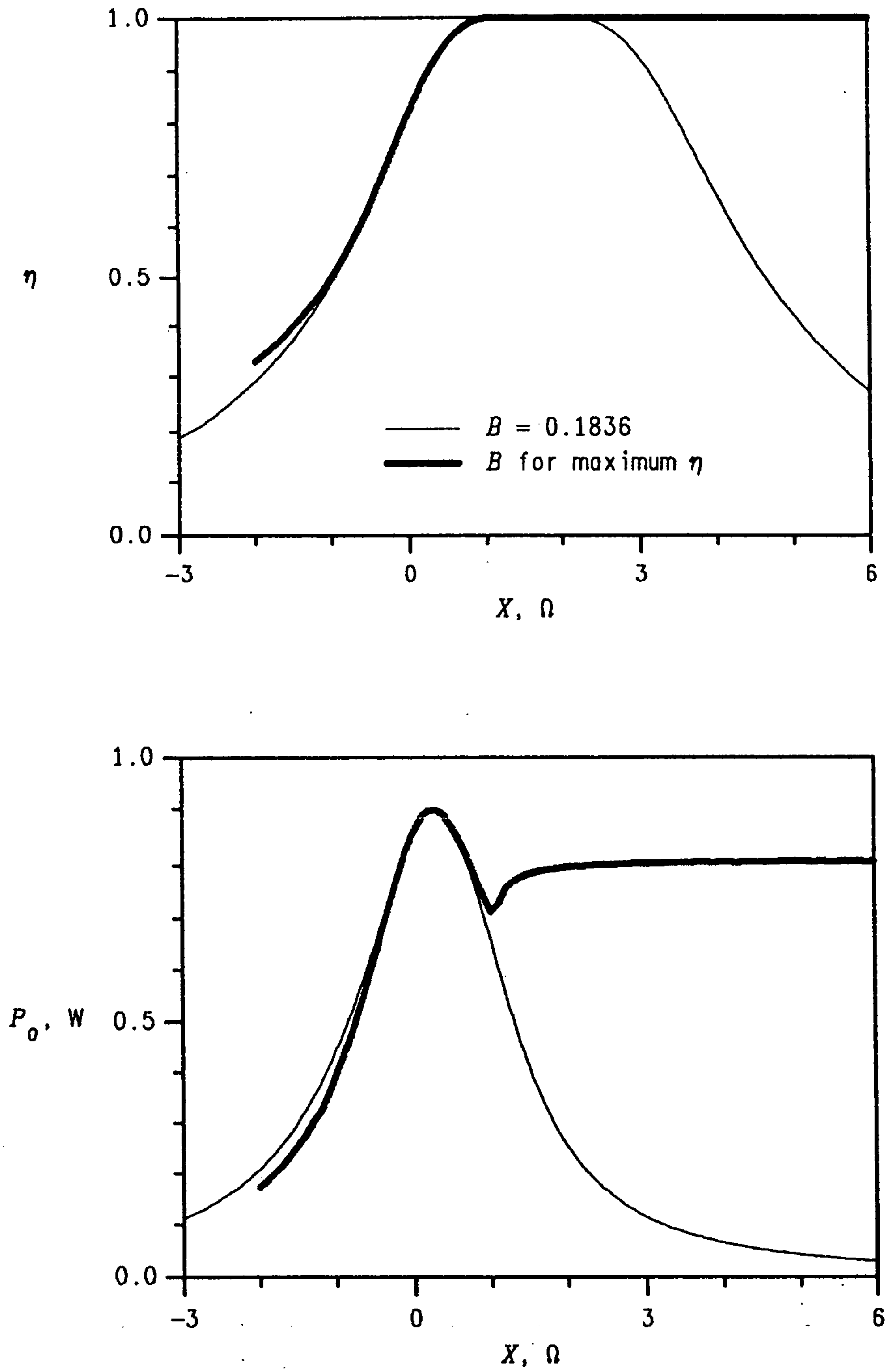

Figure 3. Effect of tuning only C1.

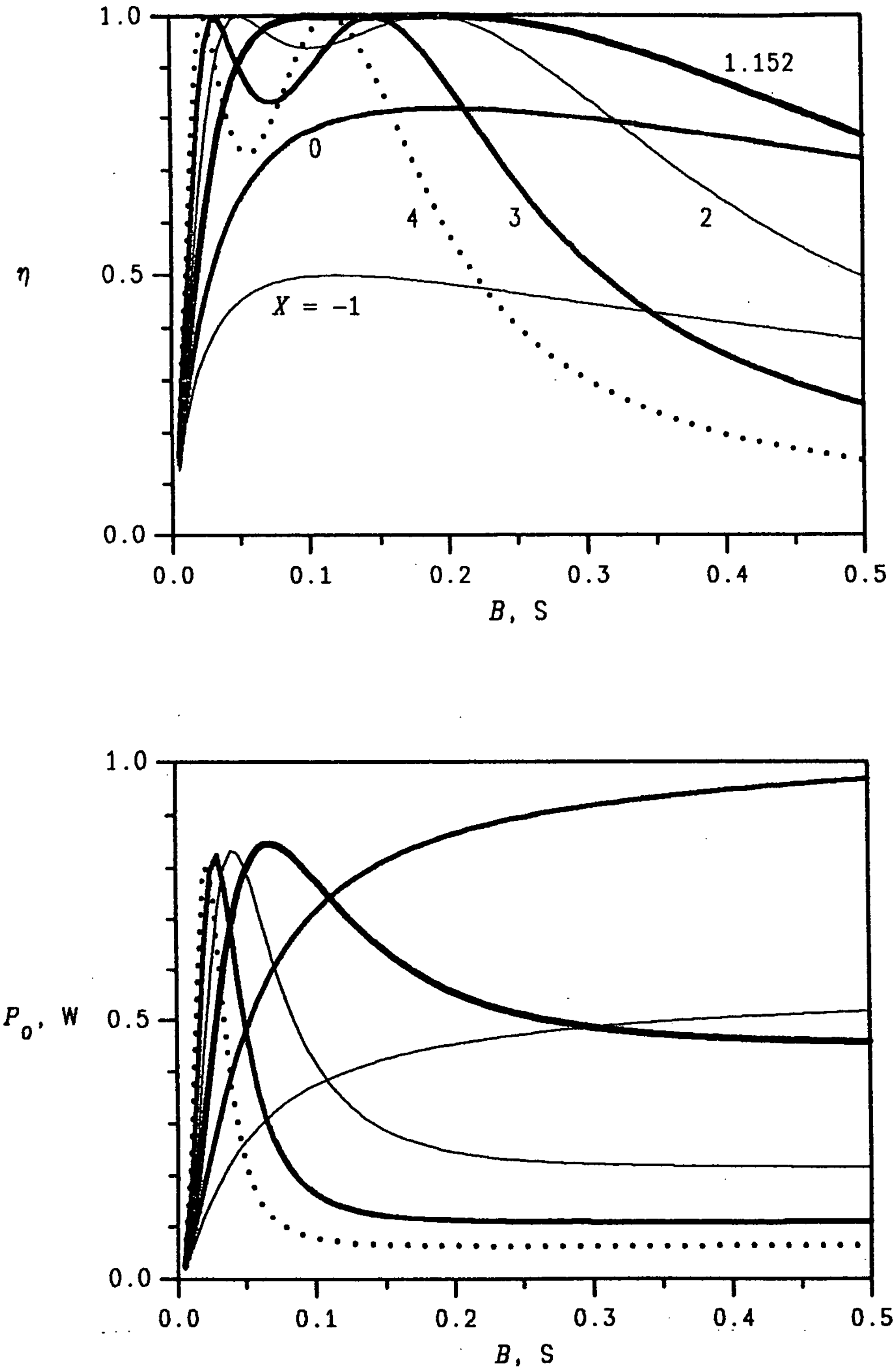

Figure 4. Effect of tuning C1 for various load reactances.

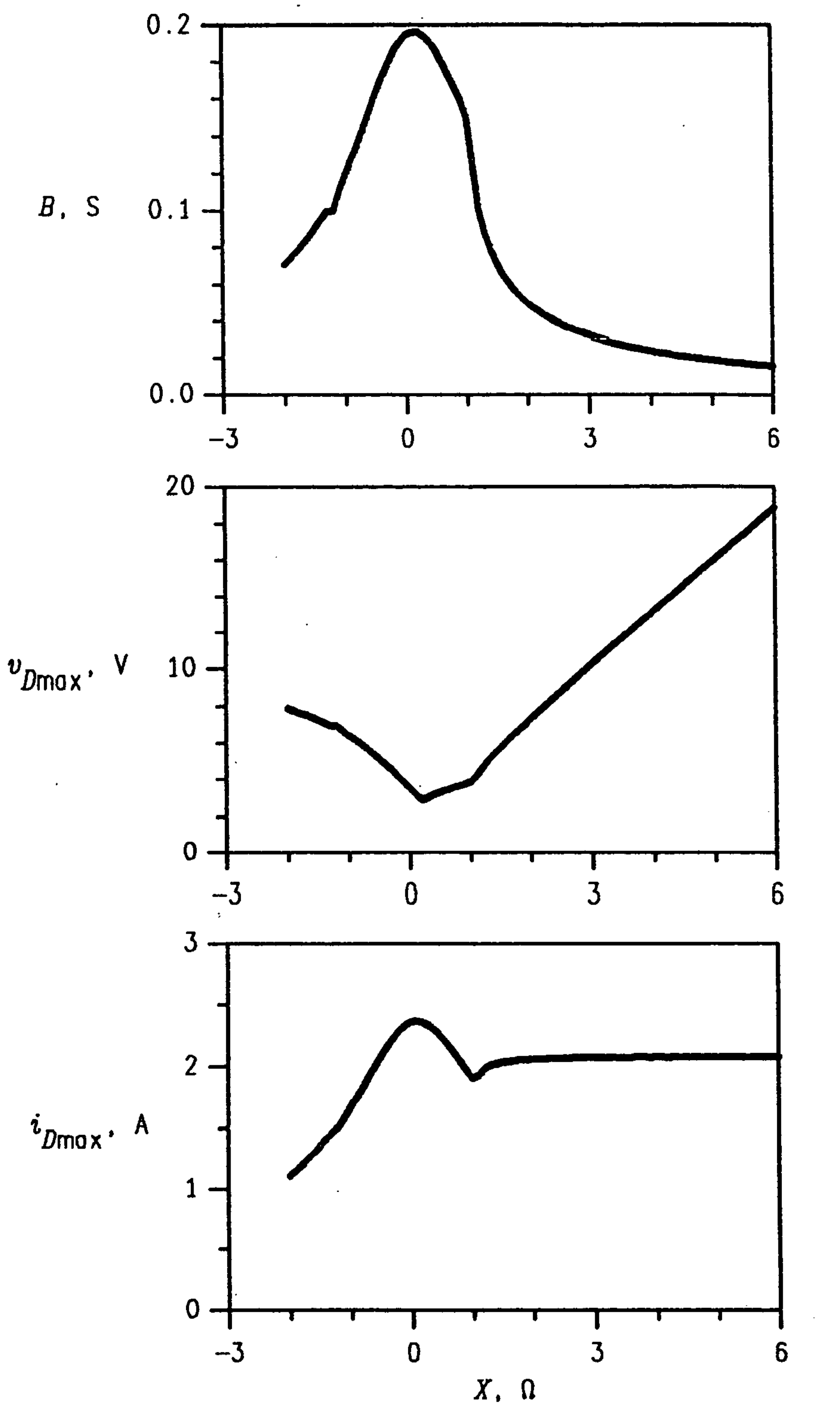

Figure 5. Optimum value of *B* and resultant peak voltage and current.

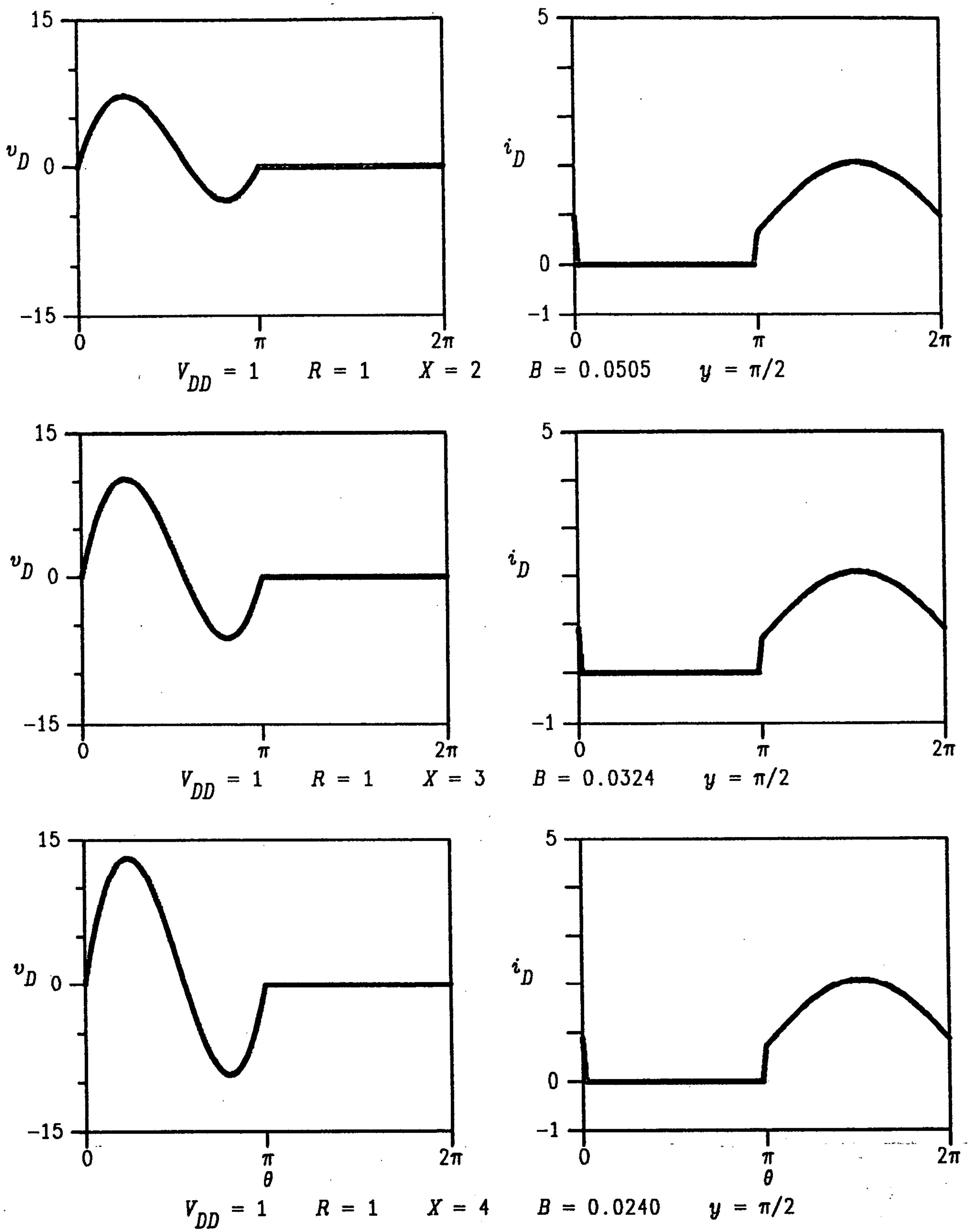

Figure 6. Waveforms for tuning only C1.

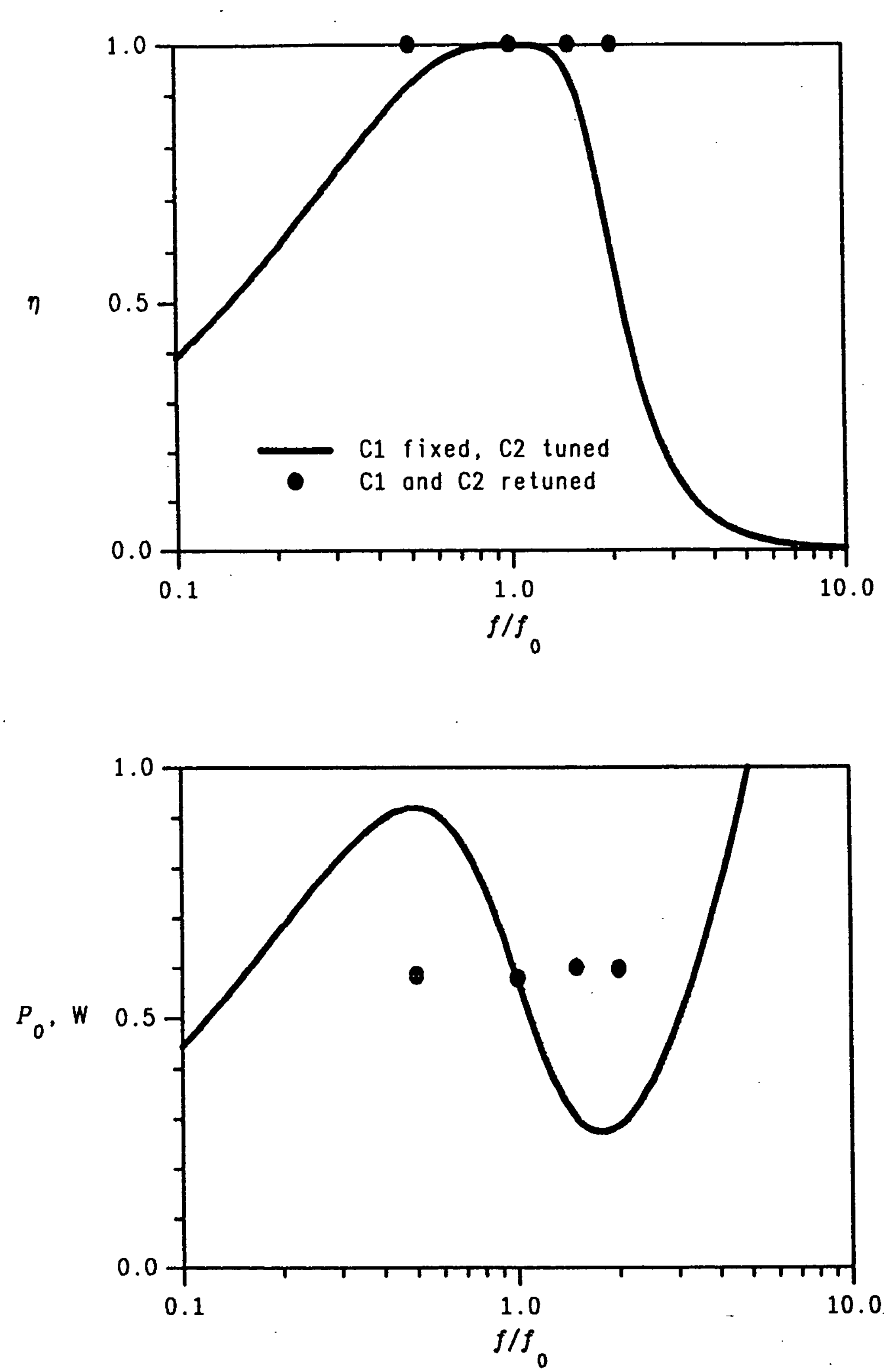

Figure 7. Effect of tuning both C1 and C2.

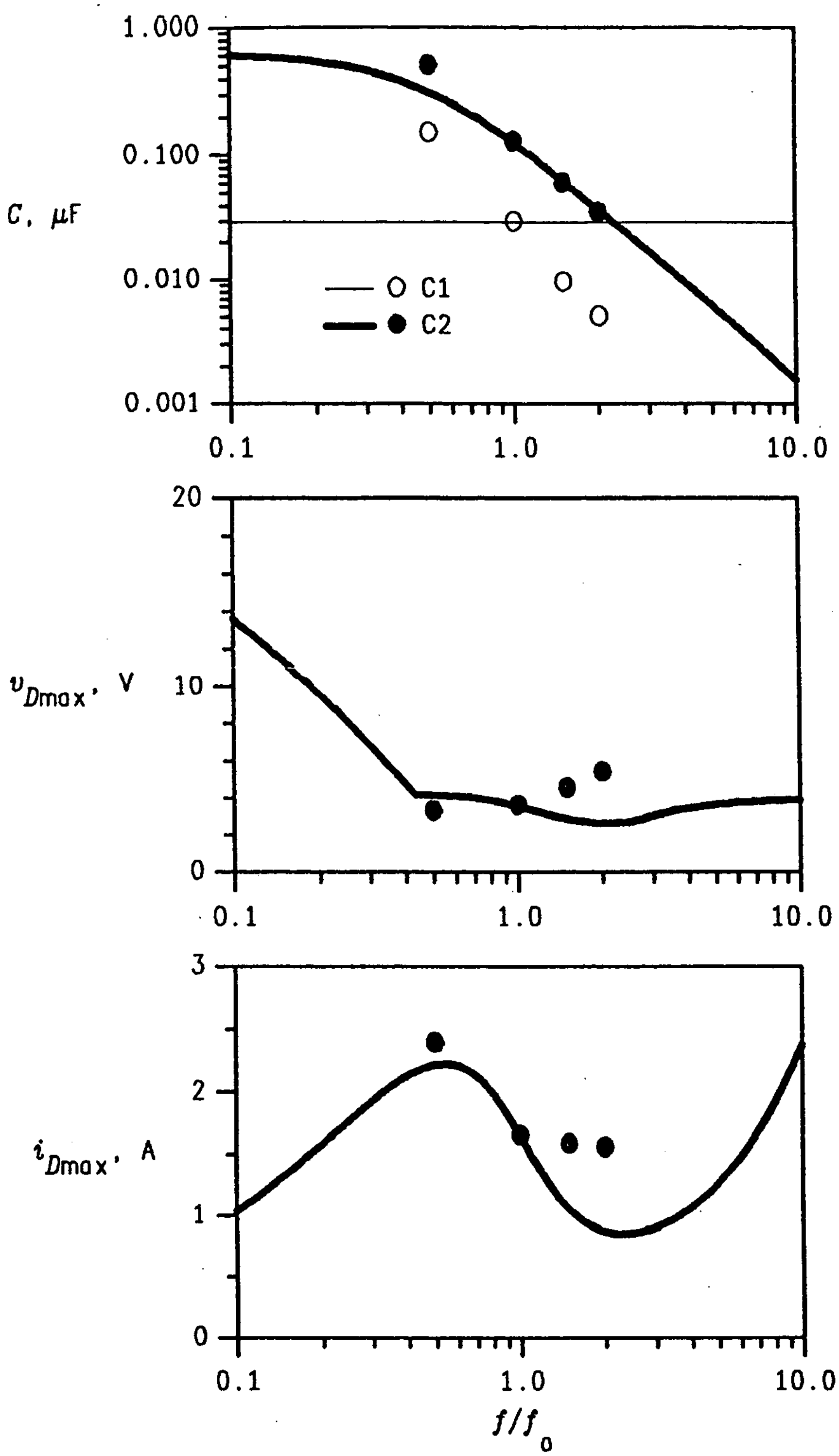

Figure 8. Optimum values of C1 and C2 and resultant v_{Dmax} and i_{Dmax}.

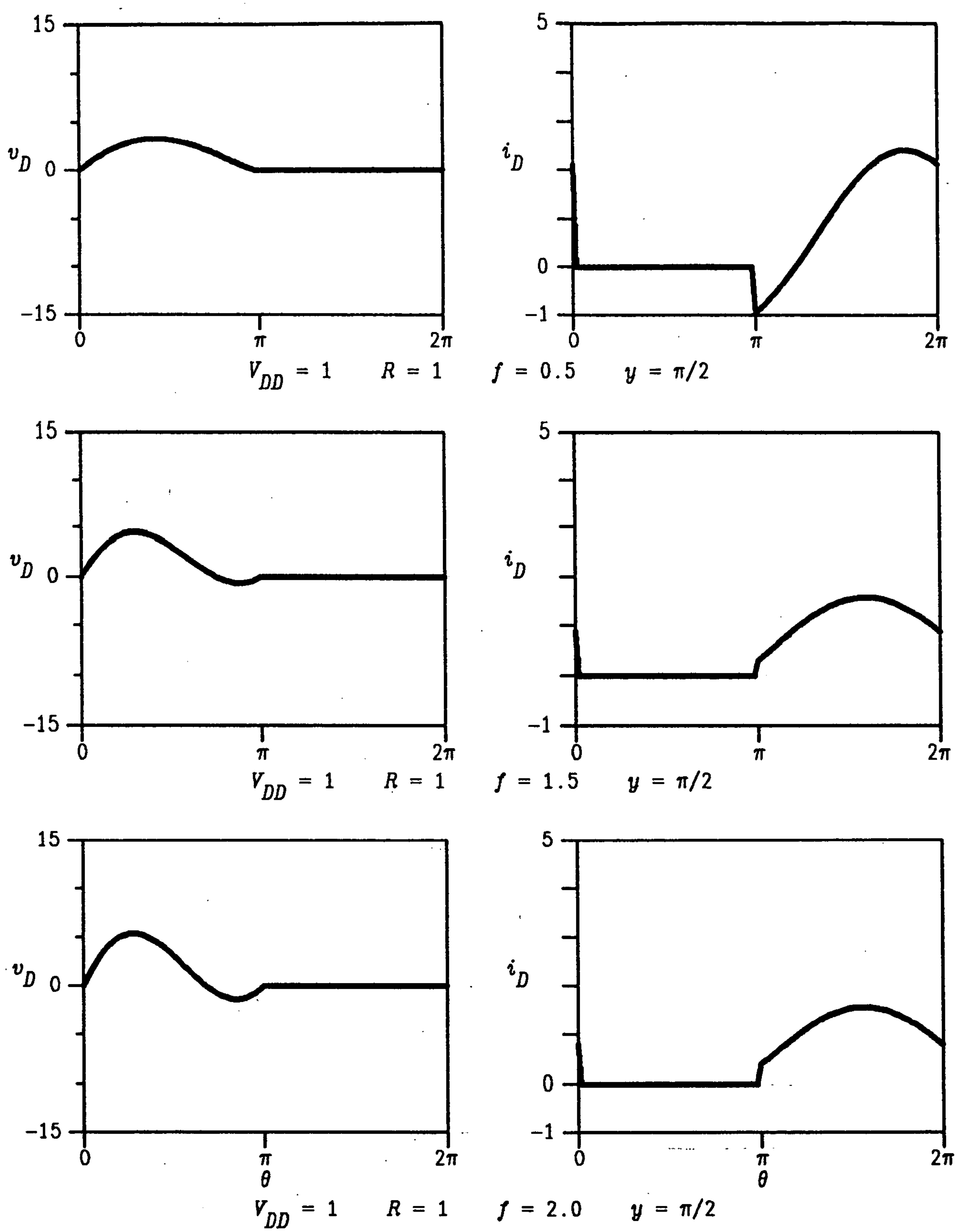

Figure 9. Waveforms for tuning both C1 and C2.